ARMY RESEARCH LABORATORY

Final Report (2005)

U.S. Army Research Laboratory
Material Center of Excellence

Collaborative Research Program on Advanced Metals and Ceramics for Armor and Anti-Armor Applications

Dynamic Behavior of Non-Crystalline and Crystalline Metallic Systems

by K. T. Ramesh and James W. McCauley

ARL-CR-576 **September 2006**

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under contract

DAAD19-01-2-0003

NOTICES

Disclaimers

Army Research Laboratory

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
September 2006	Final	1 January 2001–31 December 2005

4. TITLE AND SUBTITLE
Final Report (2005), U.S. Army Research Laboratory Material Center of Excellence, Collaborative Research Program on Advanced Metals and Ceramics for Armor and Anti-Armor Applications, Dynamic Behavior of Non-Crystalline and Crystalline Metallic Systems

5a. CONTRACT NUMBER
DAAD19-01-2-0003

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
K. T. Ramesh and James W. McCauley

5d. PROJECT NUMBER
BH64

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Johns Hopkins University
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Baltimore, MD 21218

U.S. Army Research Laboratory
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Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM
Aberdeen Proving Ground, MD
21005-5069

10. SPONSOR/MONITOR'S ACRONYM(S)
ARL-CR-576

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This collaborative research program emphasized collaborative research between Johns Hopkins University and the U.S. Army Research Laboratory (ARL) towards well-defined common goals: the understanding and development of advanced metallic systems for armor and anti-armor applications. The Johns Hopkins side of the collaboration was operated through a science-driven, problem-directed Center—the Center for Advanced Metal and Ceramic Systems. The Center provides a tight integration of the University with ARL, providing both an emphasis on fundamentals and a carefully planned coherent assistance with the ARL Weapons and Materials Research Directorate (WMRD) mission. The research thrusts and the collaborative structures of the Center provided a basis for the substantial enhancement and continuous improvement of the scientific and technical capabilities of ARL, particularly of WMRD. Each research thrust operated a Collaborative Research Group with joint responsibility for the development of the research.

This report is the final report for research performed in the 2001–2005 period. The accomplishments of each research thrust are described in order. Rather than provide full detail in each case, the highlights are noted, and the corresponding publications are referenced for the details. Finally, a summary of the collaborative interactions and a summary of the publications and presentations are provided.

15. SUBJECT TERMS
dynamic properties, metals, bulk metallic glass, nanostructured metals

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					James W. McCauley
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (*Include area code*)
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	36	410-306-0711

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Preface

Research was sponsored by the U.S. Army Research Laboratory (ARL) (ARMAC-RTP) and was accomplished under the ARMAC-RTP contract number DAAD19-01-2-0003. The views and conclusions contained in this report are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of ARL or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon.

1. Introduction

This collaborative research program emphasized collaborative research between Johns Hopkins University (JHU) and the U.S. Army Research Laboratory (ARL) towards well-defined common goals: the understanding and development of advanced metallic systems for armor and anti-armor applications. The Johns Hopkins side of the collaboration was operated through a science-driven, problem-directed Center—the Center for Advanced Metal and Ceramic Systems (CAMCS). The Center provides a tight integration of the University with ARL, providing both an emphasis on fundamentals and a carefully planned coherent assistance with the ARL Weapons and Materials Research Directorate (WMRD) mission. The research thrusts and the collaborative structures of the Center provided a basis for the substantial enhancement and continuous improvement of the scientific and technical capabilities of ARL, and particularly of WMRD. Each research thrust operated a Collaborative Research Group (CRG) with joint responsibility for the development of the research.

This report is the final report for research performed in the 2001–2005 period. The accomplishments of each research thrust are described in order. Rather than provide full detail in each case, the highlights are noted and the corresponding publications are referenced for the details. Finally, a summary of the collaborative interactions and a summary of the publications and presentations are provided.

2. Metal-Matrix Composites Research Thrust

Core Faculty: K. T. Ramesh, Jean-Francois Molinari, Y. Li (Visiting Prof.)

ARL Collaborators: E. S. C. Chin, M. Scheidler, G. Gazonas, T. W. Wright, J. McCauley

Junior Personnel: H. Zhang (Ph.D. student), Dr. S. P. Joshi (Postdoc)

2.1 Long-Range Objectives

The primary long-range objective was to understand the influence of microstructure on the high-strain-rate behavior and dynamic failure of metal-ceramic composites, including size effects and multiaxial loading effects. This was coupled with computational simulations and experimental evaluation of the response and failure of graded composite structures under impact, including objective oriented optimization and the estimation of damage under dynamic loading.

2.2 Selected Accomplishments

Failure mechanisms in dynamic tension of several metal-matrix composites and the associated un-reinforced alloys were examined (figure 1). Microscopic examinations showed that the conventional view that dynamic tensile failure of these composites is always associated with particle fracture must be revised—the type of matrix and processing route can make critical differences to behavior.[1]

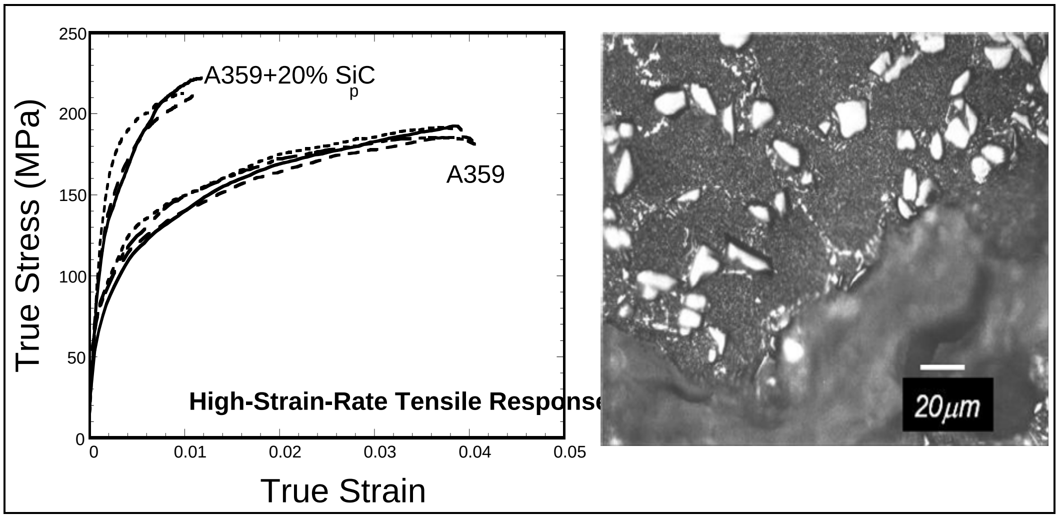

Figure 1. High-strain-rate tension of A359-based composite showing work-hardening and (at right) micrograph showing no SiC particle fracture.

OOF-based simulation methods for wave propagation problems in metal-matrix composites with real particle distributions were developed. Figure 2 shows the von Mises stress distribution for metal-matrix composite elastic-viscoplastic models, with different particle sizes and with real material microstructure, under dynamic loading. Simulation results show that even though significant stress concentration exists for irregular shape particles in the real microstructure model, the overall dynamic response is similar to that of models including simplified spherical shape particles.[2]

Experimentally-validated models for the effect of interface properties on the dynamic response of metal-matrix composites to multiaxial loading were developed (figure 3). The interface response was shown to have a strong effect on the tension-compression asymmetry.[3]

---

[1]Li, Y.; Ramesh, K. T.; Chin, E. S. C. Comparison of the Plastic Deformation and Failure of A359/SiC and 6061-T6/Al_2O_3 Metal Matrix Composites under Dynamic Tension. *Mat. Science and Eng. A.* **2004**, *371*, 359–370.

[2]Zhang, H. Ph.D. Dissertation, Johns Hopkins University, Baltimore, MD, 2005.

[3]Zhang, H.; Ramesh, K. T.; Chin, E. S. C. Effects of Interfacial Debonding on the Rate-Dependent Response of Metal Matrix Composites. Acta Materialia, in press, 2005.

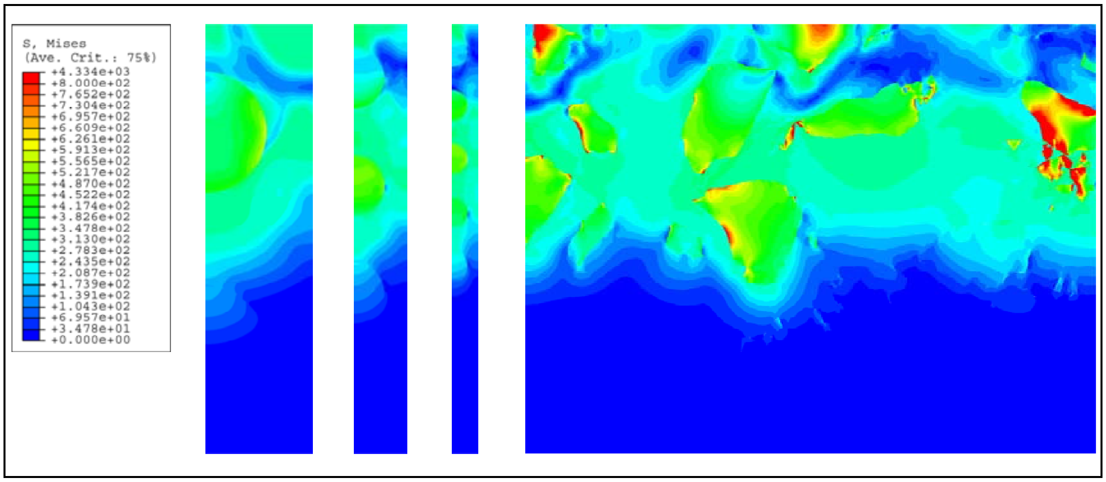

Figure 2. von Mises stress distribution (at 12 ns) for MMC elastic-viscoplastic models under a 4-ns span, 1 GPa amplitude dynamic load on the top surface. Models are with different particle sizes: 40, 20, and 10 μm and with a real material microstructure.

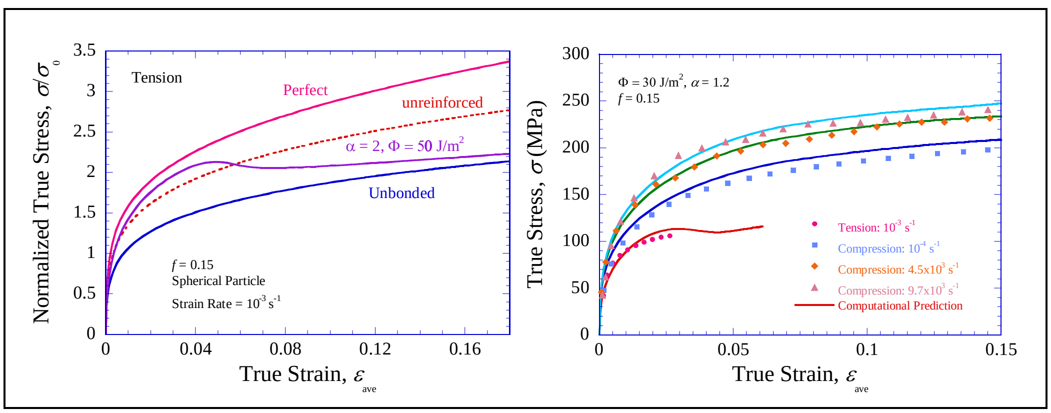

Figure 3. (a) Typical tensile stress-strain curve predicted by the model with imperfect interface ($\alpha = 2$ and $\Phi = 50$ J/m^2), compared with the limit cases and unreinforced matrix material. (b) Comparison with experiment Al6092/B_4C_p.

The first high-strain-rate experimental results on a ceramic-reinforced nano-micro aluminum-based composite (figure 4) were obtained, showing dynamic strengths only 20% lower than that of rolled homogenous armor (RHA) at approximately one-third the weight.[4]

Models for wave propagation through graded and layered structures were developed, with a view towards use of metal-matrix composite backings for ceramic armor.

[4]Zhang, H.; Ramesh, K. T.; Ye, J.; Schoenung, J.; Chin, E. S. C. Nanoengineering Aluminum for Strength Under Impact, in preparation.

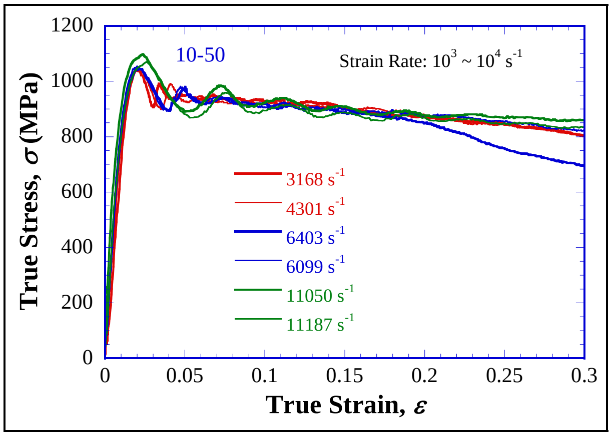

Figure 4. High-strain-rate compressive response of aluminum-based nano-micro composite showing remarkable strength for an aluminum-weight material.

2.3 Collaborative Interactions

The Metal-Matrix Composite CRG met regularly to discuss and plan this research. Several ARL scientists attended these meetings, most multiple times. Dr. Chin was the lead ARL participant in this CRG. We also collaborated with Professor J. Schoenung of the University of California, Davis, on the nano-micro Al materials.

2.4 Publications

1. Li, Y.; Ramesh, K. T.; Chin, E. S. C. Dynamic Characterization of Layered and Graded Structures under Impulsive Loading. *International Journal of Solids and Structures* **2001**, *38* (34–35), 6045–6061.

2. Zhang, H.; Ramesh, K. T.; Chin, E. S. C. Effects of Processing on High Strain Rate Response of Boron Carbide Particulate Reinforced 6092 Aluminum. In *Affordable Metal Matrix Composites for High Performance Applications*; Pandey, A. B., Kendig, K. L., Lewandowski, J. J., Shah, S. R., Eds.; TMS: Warrendale, PA, 2003; 43–50.

3. Li, Y.; Ramesh, K. T.; Chin, E. S. C. Comparison of the Plastic Deformation and Failure of A359/SiC and 6061-T6/Al_2O_3 Metal Matrix Composites under Dynamic Tension. *Materials Science and Engineering A* **2004**, *371*, 359–370.

4. Zhou, F.; Molinari, J. F.; Li, Y. Three Dimensional Numerical Simulation of Dynamic Fracture in Silicon Carbide Reinforced Aluminum. *Engineering Fracture Mechanics* **2004**, *71*, 1357–1378.

5. Li, Y.; Ramesh, K. T.; Chin, E. S. C. The Mechanical Response of an A359/SiCp MMC and the A359 Aluminum Matrix to Dynamic Shearing Deformations. *Materials Science & Engineering A* **2004**, *382*, 162–170.

6. Li, Y.; Ramesh, K. T.; Chin, E. S. C. Plastic Deformation and Failure in A359 Aluminum and an A359/SiCp MMC under Quasistatic and High-Strain-Rate Tension. Journal of Composite Materials, in press, 2005.
7. Li, Y.; Ramesh, K. T. A Novel Technique for Accurate Measurement of Material Properties in the Tension Kolsky Bar. International Journal of Impact Engineering, in press, 2005.
8. Zhang, H.; Ramesh, K. T.; Chin, E.S.C. Effects of Interfacial Debonding on the Rate-Dependent Response of Metal-Matrix Composites. *Acta Mat.* **2005**, *53*, 4687–4700.

2.5 Student Theses/Dissertations/Graduations

Zhang, H. Fabrication, High-Strain-Rate Constitutive Behavior and Dynamic Failure of MMCs. Ph.D. Dissertation, January 2005. He is now a postdoc at the University of Texas, Austin, with Professor Ravi-Chandar.

3. Nanostructured Metals Research Thrust

Core Faculty: E. Ma, K. T. Ramesh

ARL Collaborators: R. J. Dowding, K. Cho, L. Kecskes, L. Magness, T. Wright, J. LaSalvia, J. Adams, S. Schoenfeld, E. S. C. Chin

Associate Research Scientist: Dr. Qiuming Wei

Graduate Students: Brian Schuster (ARL), D. Jia

3.1 Long-Range Objectives

- Develop an understanding of the high strain rate behavior of model nanostructured metals (bcc, fcc, hcp).
- Systematically characterize the dependence of mechanical behavior (quasistatic and dynamic) on grain size and distribution.
- Understand the active deformation modes and mechanisms and their dependence on grain size.
- Develop nanophase W-based alloys for anti-armor applications.

3.2 Selected Accomplishments

Shear localization (figure 5) in pure polycrystalline tungsten (W) under uniaxial dynamic loading was demonstrated for the first time, by introducing the appropriate nanocrystalline or ultrafine grain structure.[5] A joint Hopkins/ARL patent has been filed through ARL for the protocol developed in the JHU labs to process such microstructures.

Bulk nanostructured and ultrafine-grained bcc metals, including W, Ta, Fe, and V, were developed, and the quasistatic and dynamic deformation/fracture behavior of these metals was documented (figure 6).[6]

A dislocation-mechanism based model that explains the strain rate sensitivity behavior of these nanostructured and ultrafine-grained bcc metals was developed (figure 7). A constitutive model has been established for Fe in particular.[7]

---

[5] Wei, Q.; Jiao, T.; Ramesh, K. T.; Ma, E.; Kecskes, L. J.; Magness, L.; Dowding, R.; Kazykhanov, V. U.; Valiev, R. Z. Adiabatic Shear Localization under Uniaxial Compression in Bulk Tungsten with Ultrafine Microstructure. Acta Materialia, accepted for publication, 2005.

[6] Wei, Q.; Jiao, T.; Mathaudhu, S. N.; Ma, E.; Hartwig, K. T.; Ramesh, K. T. Microstructure and Mechanical Properties of Tantalum After Equal Channel Angular Extrusion (ECAE). *Materials Science and Engineering A* **2003**, *358*, 266–272.

[7] Jia, D.; Ramesh, K. T.; Ma, E. Effects of Nanocrystalline and Ultrafine Grain Sizes on Constitutive Behavior and Shear Bands in Iron. *Acta Materialia* **2003**, *51* (12), 3495–3509.

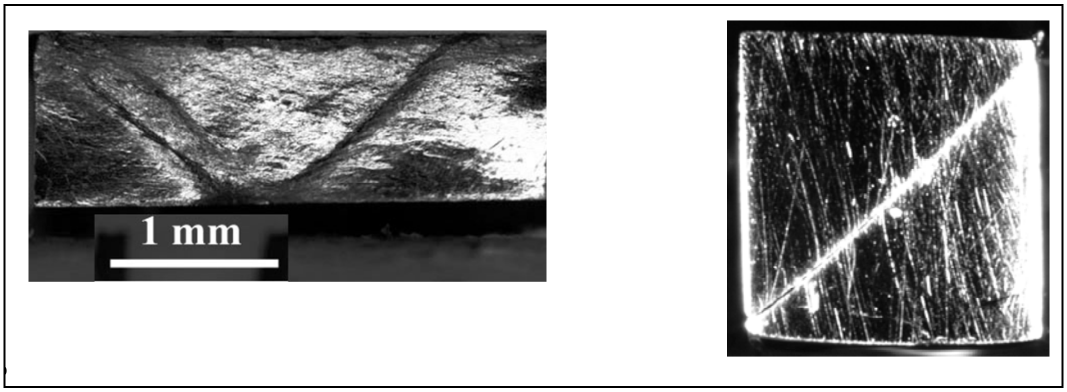

Figure 5. Optical micrographs of adiabatic shear bands in (a) ECAP+CR W and (b) HPT W after high-strain-rate uniaxial compression.

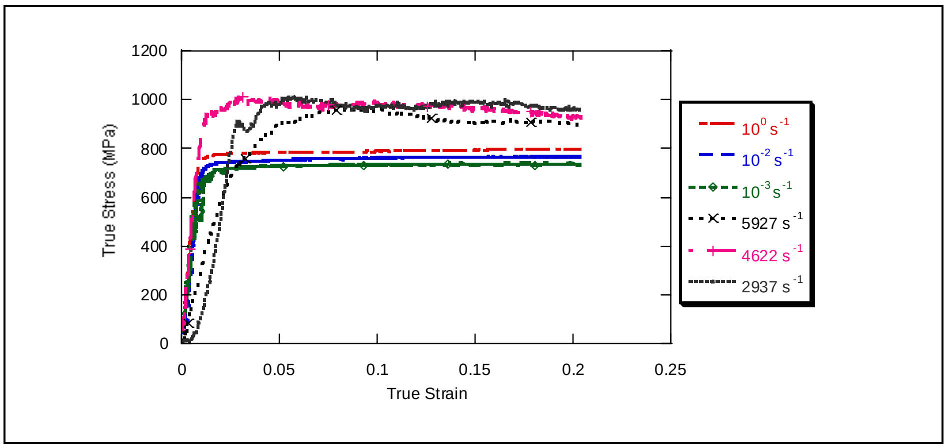

Figure 6. Rate-dependent response of ECAE tantalum (ultra-fine-grained) showing high strengths but relatively low rate-sensitivity.

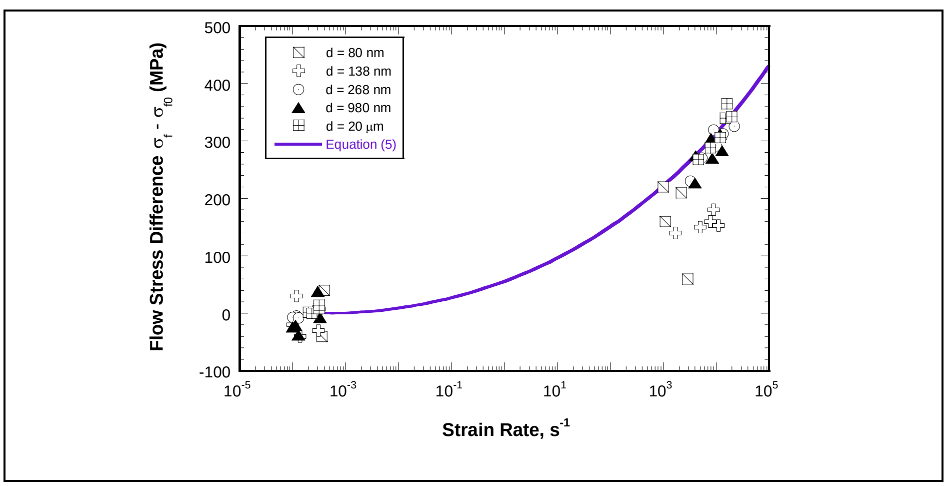

Figure 7. Rate-dependent response of bcc Fe at various grain sizes showing that while the overall rate-sensitivity is a function of the grain size, the additional strengthening due to rate is not.

Adiabatic shear banding as a dominant deformation mode in these nanostructured and ultrafine-grained bcc metals at high strain rates was demonstrated.[8]

Reduced strain rate sensitivity (figure 8) of nanostructured and ultrafine-grained bcc metals in comparison with their conventional coarse-grained counterparts was demonstrated.[9]

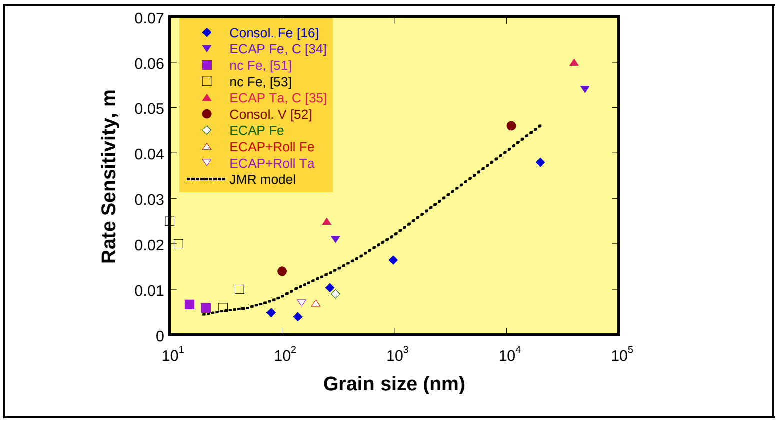

Figure 8. The effective rate-sensitivity of bcc metals appears to decrease with grain size as a result of the dislocation mechanisms relevant in these materials.

The elevated strain rate sensitivity in nanostructured and ultrafine grained fcc metals was explored. A model explanation has been published on this behavior.[9]

3.3 Publications

1. Jia, D.; Wang, Y.; Ramesh, K. T.; Ma, E.; Zhu, Y. T.; Valiev, R. Deformation Behavior and Plastic Instability of Ultrafine Grained Ti. *Appl. Phys. Lett.* **2001**, *79*, 611–613.

2. Jia, D.; Ramesh, K. T.; Ma, E.; Lu, L.; Lu, K. Compressive Behavior of an Electrodeposited Nanostructured Copper at Quasistatic and High Strain Rates. *Scripta Materialia* **2001**, *45*, 613–620.

3. Jia, D.; Ramesh, K. T.; Ma, E. Effects of Nanocrystalline and Ultrafine Grain Sizes on Constitutive Behavior and Shear Bands in Iron. *Acta mater*. **2003**, *51*, 3495.

4. Wei, Q.; Jiao, T.; Hartwig, T.; Ma, E.; Ramesh, K. T. Microstructure and Mechanical Properties of Tantalum After Equal Channel Angular Extrusion (ECAE). *Mater. Sci. Eng. A* **2003** *358*, 266.

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[8]Wei, Q.; Ramesh, K. T.; Ma, E.; Kesckes, L. J.; Dowding, R. J.; Kazykhanov, V. U.; Valiev, R. Z. Plastic Flow Localization in Bulk Tungsten With Ultrafine Microstructure. *Applied Physics Letter* **2005**, *86*, 101907.

[9] Wei, Q.; Wang, Y. M.; Ramesh, K. T.; Ma, E. Effects of Nanocrystalline and Ultrafine Grain Sizes on the Strain Rate Sensitivity: fcc vs. bcc Metals. *Materials Science & Engineering A* **2004**, *381* (1–2), 71–79.

5. Wei, Q.; Jiao, T.; Ramesh, K. T.; Ma, E. Nano-Structured Vanadium: Processing and Mechanical Properties Under Quasi-Static and Dynamic Compression. *Scripta Mater.* **2004**, *50*, 359.

6. Wei, Q.; Kecskes, L.; Jiao, T.; Hartwig, K. T.; Ramesh, K. T.; Ma, E. Adiabatic Shear Banding in Ultrafine-Grained Fe Processed by Severe Plastic Deformation. *Acta materialia* **2004**, *52*, 1859.

7. Wei, Q.; Cheng, S.; Ma, E.; Ramesh, K. T. Effect of Nanocrystalline and Ultrafine Grain Sizes on the Strain Rate Sensitivity and Activation Volume: FCC vs. BCC Metals. *Materials Science & Engineering A* **2004**, *381*, 71–79.

8. Wei, Q.; Ramesh, K. T.; Ma, E.; Kesckes, L. J.; Dowding, R. J.; Kazykhanov, V. U.; Valiev, R. Z. Plastic Flow Localization in Bulk Tungsten with Ultrafine Microstructure. *Applied Physics Letters* **2005**, *86*, 101907.

3.4 Student Theses/Dissertations/Graduations

Jia, D. The Mechanical Behavior of Nanostructured Materials. Ph.D. Dissertation, June 2001.

4. Bulk Amorphous Metals Research Thrust

Core Faculty: T. C. Hufnagel, K. T. Ramesh, E. Ma

ARL Collaborators: L. Kecskes, R. Woodman, L. Magness, T. W. Wright, J. Adams, R. Adler, R. J. Dowding, K. Cho, S. Schoenfeld, K. Doherty

Postdoctoral Associates: T. Jiao, Jiaping Wang, David Horspool

Graduate Students: R. T. Ott

4.1 Long-Range Objectives

- Develop a fundamental understanding of the dynamic behavior of bulk amorphous alloys and composites, including processing, quasistatic and dynamic characterization, and microstructural characterization.
- Understand the dynamic deformation and failure mechanisms within bulk amorphous alloys.
- Develop a high density bulk metallic-glass matrix composite material, fully characterized at high strain rates, for anti-armor applications.

4.2 Selected Accomplishments

A novel technique for producing in situ metallic glass-matrix composites (MGMCs) was developed, which was patented with both JHU and ARL investigators as co-inventors. Using this technique, we produced a series of MGMCs with dramatically enhanced plastic strain to failure in compression as well as limited ductility in tension (figure 9).[10]

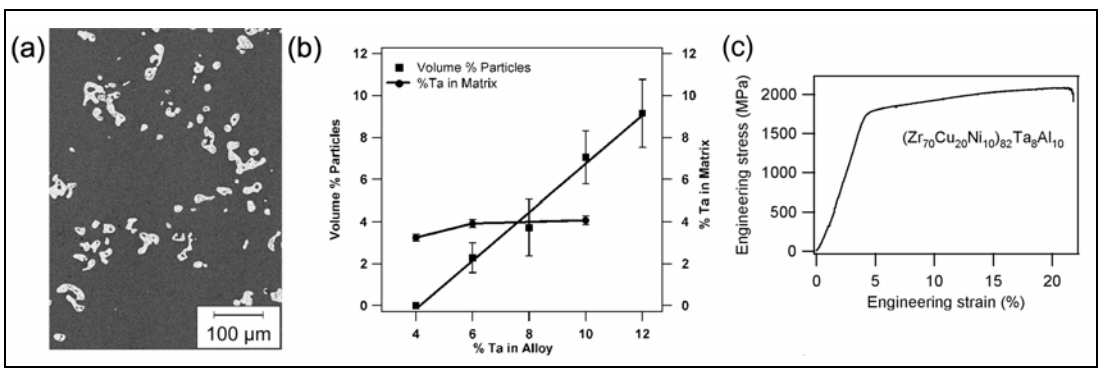

Figure 9. (a) Microstructure of $(Zr_{70}Cu_{20}Ni_{10})_{82}Ta_8Al_{10}$) in situ metallic glass-matrix composite (MGMC). (b) Volume fraction and matrix composition of in situ MGMCs. (c) Quasistatic compression of in situ composite showing dramatically enhanced plastic strain to failure.

[10]Xing, L.-Q.; Li, Y.; Ramesh, K. T.; Li, J.; Hufnagel, T. C. Enhanced Plastic Strain in Zr-Based Bulk Amorphous Alloys. *Phys. Rev. B* **2001**, *64*, 180201(R).

The first in situ x-ray diffraction studies of strain evolution during deformation of in situ MGMCs were performed. Among other things, this work showed that shear band initiation in MGMCs (with ductile reinforcements) occurs due to the development of stress concentrations around the particles that arise due to a plastic misfit strain between the particles and matrix.[11]

The mechanical behavior of several single-phase metallic glasses under both dynamic and quasistatic compression, including real-time cinematography of failure under dynamic compression, was evaluated. The results (figure 10) clearly show that the failure stress of single-phase glasses is essentially constant up to strain rates of about 10^1 s^{-1}, but decreases with increasing strain rate for rates above about 10^2 s^{-1}. We attributed the dynamic behavior to the increasing effects of thermal softening in the shear bands at high rates.[12]

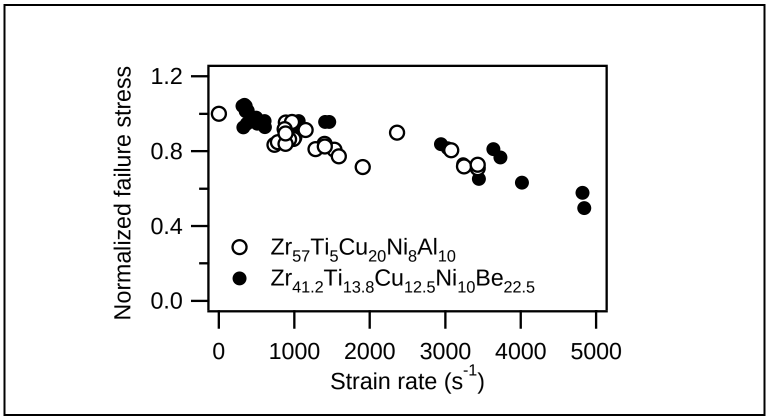

Figure 10. Dependence of failure strength (normalized by that under quasistatic loading) on strain rate for two bulk amorphous alloys: $Zr_{57}Ti_5Cu_{20}Ni_8Al_{10}$ (this work) and $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (Bruck et al., 1996)[13].

The mechanical behavior of both in situ and ex situ MGMCs including substantial amounts of tungsten under dynamic and quasistatic compression was evaluated. Unlike single-phase metallic glasses, MGMCs with 60 vol. % tungsten particle reinforcement behave as strain-hardening materials. Furthermore, the MGMCs exhibit significant plastic strain before failure because the particle both initiate shear bands and impede their propagation, thereby distributing plastic strain more effectively. Final fracture occurs due to adiabatic shear localization. MGMCs with small volume fractions of particles (<10%) have dynamic behavior quite similar to that of single-phase glasses, despite the significant difference in quasistatic behavior.[14]

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[11] Ott, R. T.; Sansoz, F.; Molinari, J.-F.; Almer, J.; Ramesh, K. T.; Hufnagel, T. C. Micromechanics of Deformation of Metallic-Glass-Matrix Composites From In Situ Synchrotron Strain Measurements and Finite Element Modeling. *Acta Mater* **2005**, *53*, 1883–1893.
[12] Jiao, T.; Fan, C.; Kecskes, L. J.; Hufnagel, T. C.; Ramesh, K. T. Effect of Loading Rate in Bulk Metallic Glasses. *Materials Research Society Symposium Proceedings* **2003**, *754*, 6.2.1–6.2.6.
[13] Bruck, A.; Rosakis, A. J.; Johnson, J. *J. Materials Research* **1996**, *11*, 503.
[14] Jiao, T.; Kecskes, L. J.; Hufnagel, T. C.; Ramesh, K. T. Deformation and Failure of Zr57Nb5Al10Cu15.4Ni12.6 Metallic Glass/W Particle Composites Under Quasi-Static and Dynamic Compression. *Met. Mat. Trans. A* **2004**, *35*, 3439–3444.

4.3 Collaborative Interactions

The Bulk Amorphous Metals CRG met regularly to discuss and plan this research. Laszlo Kecskes (ARL) worked extensively in the Hopkins laboratories, preparing bulk amorphous samples and collaborating with Dr. Cang Fan on the characterization of amorphous alloys.

4.4 Publications

1. Xing, L.-Q.; Hufnagel, T. C. Plastic Deformation of Bulk Amorphous Alloys. *MRS Symp. Proc.* **2001**, *644*, L11.7.1–11.7.6.

2. Gu, X.; Xing, L.-Q., Hufnagel, T. C. Preparation and Mechanical Properties of Hafnium-Based Bulk Metallic Glasses. *MRS Symp. Proc.* **2001**, *644*, L12.16.1–12.16.6.

3. Xing, L.-Q.; Li, Y.; Ramesh, K. T.; Li, J. Hufnagel, T. C. Enhanced Plastic Strain in Zr-Based Bulk Amorphous Alloys. *Phys. Rev. B* **2001**, *64*, 180201(R).

4. Hufnagel, T. C.; Xing, L.-Q.; Li, Y.; Jia, D.; Ramesh, K. T. Deformation and Failure of Bulk Amorphous $Zr_{57}Ti_5Cu_{20}Ni_8Al_{10}$ Under Quasi-Static and Dynamic Compression. *Journal of Materials Research* **2002**, *17*, 1441.

5. Gu, X.; Xing, L.-Q.; Hufnagel, T. C. Preparation and Glass Forming Ability of Bulk Metallic Glass $(Hf_xZr_{1-x})_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$. *J. Non-Cryst. Solids* **2002**, *311*, 77.

6. Hufnagel, T. C.; Fan, C.; Ott, R. T.; Li, J.; Brennan, S. Controlling Shear Band Behavior in Metallic Glasses Through Microstructural Design. *Intermetallics* **2002**, *10* (11–12), 1163-1166.

7. Gu, X.; Jiao, T.; Kecskes, L. J.; Woodman, R. H.; Fan, C.; Ramesh, K. T.; Hufnagel. T. C. Crystallization and Mechanical Behavior of (Hf, Zr)-Ti-Cu-Ni-Al Metallic Glasses *J. Non-Cryst. Solids* **2003**, *317*, 112.

8. Jiao, T.; Fan, C.; Kecskes, L. J.; Hufnagel, T. C.; Ramesh, K. T. Effect of Loading Rate in Bulk Metallic Glasses. *Materials Research Society Symposium Proceedings* **2003**, *754*, CC6.2.1-6.2.6.

9. Jiao, T.; Kecskes, L. J.; Hufnagel, T. C.; Ramesh, K. T. Deformation and Failure of $Zr_{57}Nb_5Al_{10}Cu_{15.4}Ni_{12.6}$ Metallic Glass/W Particle Composites Under Quasi-Static and Dynamic Compression. *Met. Mat. Trans. A* **2004**, *35* (11), 3439–3444.

10. Ott, R. T.; Sansoz, F. J.; Molinari, F.; Almer, J.; Fan, C.; Hufnagel, T. C. Synchrotron Strain Measurements for In Situ Formed Metallic Glass Matrix Composites; Busch, R., Hufnagel, T. C., Eckert, J., Inoue, A., Johnson, W. L., Yavari, A. R., Eds. *Mat. Res. Soc. Symp. Proc.* **2004**, *806*, 361–366.

11. Jiao, T.; Kecskes, L .J.; Hufnagel T. C.; Ramesh, K.T. Deformation and Failure of $Zr_{57}Nb_5Al_{10}Cu_{15.4}Ni_{12.6}$/W Particle Composites Under Quasistatic and Dynamic Compression. *Metallurgical and Materials Transactions* **2004**, *35* (11), 3439–3444.

12. Ott, R. T.; Sansoz, F.; Molinari, J.-F.; Almer, J.; Ramesh, K. T.; Hufnagel, T. C. Micromechanics of Deformation of Metallic-Glass-Matrix Composites From In Situ Synchrotron Strain Measurements and Finite Element Modeling. *Acta Materialia* **2005**, *53*, 1883–1893.

13. Hufnagel, T. C.; Ott, R. T.; Almer, J. Structural Aspects of Elastic Deformation of a Metallic Glass. *Physical Review B* **2006**, *73*, 064204.

4.5 Student Theses/Dissertations/Graduations

Ott, R. T. Graduated August 2004 (Ph.D.) Now a post-doctoral scholar at Ames Laboratory. Dissertation title: Processing, Structure and Properties of In Situ Formed Metallic Glass Matrix Composites.

5. Dynamic Failure and Damage Mechanisms Research Thrust

Core Faculty: Jean-Francois Molinari, K.T. Ramesh

ARL Collaborators: T. W. Wright, S. Schoenfeld, E. S. C. Chin, G. Gazonas, J. McCauley, R. J. Dowding, T. Weerasooriya, L. Magness, M. Raftenberg, T. Bjerke

Associate Research Scientist: Dr. Fenghua Zhou

Graduate Student: R. Raghupathy

5.1 Long-Range Objectives

- Characterize micromechanisms of dynamic failure developed within the other CAMCS thrusts.
- Develop mechanism-based models for the evolution of damage within heterogeneous materials under dynamic loading.
- Develop a robust modeling and simulation capability for physically realistic simulations of impact and penetration of advanced metals and metal-matrix composite systems.
- Develop a physics-based model for the dynamic nucleation, growth, and coalescence of voids in ductile metals.

5.2 Selected Accomplishments

The modeling efforts within the dynamic failure and damage mechanisms research thrust have taken two separate, yet complementary, tracks: numerical developments and simulations of dynamic failure, and models targeting the physics of damage mechanisms in connection to materials.

- An important contribution of the research has been to improve the state-of-the-art of simulations of dynamic failure and damage mechanisms. An explicit dynamic parallel code has been developed to track damage mechanisms in the form of shear bands and microcracks in two-dimensional (2-D) and three-dimensional (3-D) metallic and bulk amorphous microstructures.[15]
- Techniques to address mesh dependency in simulations of fracture using cohesive elements were developed.[16]

[15]Zhou, F.; Molinari, J. F. 3-D Finite Element Analysis of Impact Damage in Metallic and Ceramic Targets. *Ceramic Armor Materials by Design, Ceramic Transactions* **2002**, *134*, 317–328.
[16]Zhou, F.; Molinari, J. F. Dynamic Crack Propagation with Cohesive Elements: A Methodology to Address Mesh Dependency. *International Journal Numerical Methods in Engineering* **2004**, *59* (1), 1–24.

- Stochastic aspects of fracture in ceramic materials were addressed by incorporating Weibull or other distributions of strength.[1]
- A dynamic model (figure 11) for the fragmentation of brittle materials over a range of strain rates was developed, including at very high strain rates.[2]

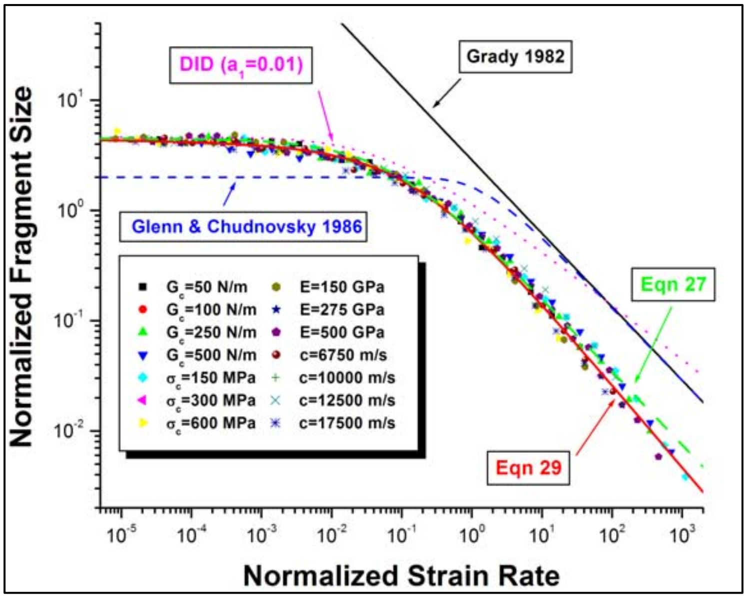

Figure 11. Calculated nondimensional fragment size vs. nondimensional strain-rate for all of the material properties examined. The predictions of other theories are included for comparison.

- We have developed a model for the dynamic growth of voids under transient loading, including the effects of strain hardening, rate sensitivity, and thermal conduction.[3] This model has been used to develop estimates (figure 12) for the spall strength of engineering materials that is a conservative estimate when compared with experiment.[4] The approach has then been extended to account for void-void interactions and to estimating the pressure-porosity relationship as a function of assumed defect distributions.
- From a physics viewpoint, the modeling efforts have investigated multiple damage mechanisms, including void growth, shear banding, and microcracking. We have established phenomenological laws to capture these mechanisms at the macroscale, and more recently, we have investigated the links between these damage mechanisms and microstructural details, including inclusions, pores, and grain boundaries.

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[1] Zhou, F.; Molinari, J. F. Stochastic Fracture of Ceramics Under Dynamic Tensile Loading. *International Journal of Solids and Structures* **2004**, *41*, 6573–6596.

[2] Zhou, F.; Molinari, J. F.; Ramesh, K. T. A Cohesive-Model Based Fragmentation Analysis: Effects of Strain Rate and Initial Defects Distribution. *International Journal of Solids and Structures* **2005**, *42*, 5181–5207.

[3] Wu, X. Y.; Ramesh, K. T.; Wright, T. W. The Dynamic Growth of a Single Void in a Viscoplastic Material Under Transient Hydrostatic Loading. *Journal of the Mechanics and Physics of Solids* **2003**, *51* (1), 1–26.

[4] Wu, X. Y.; Ramesh, K. T.; Wright, T. W. The Effects of Thermal Softening and Heat Conduction on the Dynamic Growth of Voids. *International Journal of Solids and Structures* **2003**, *40* (17), 4461–4478.

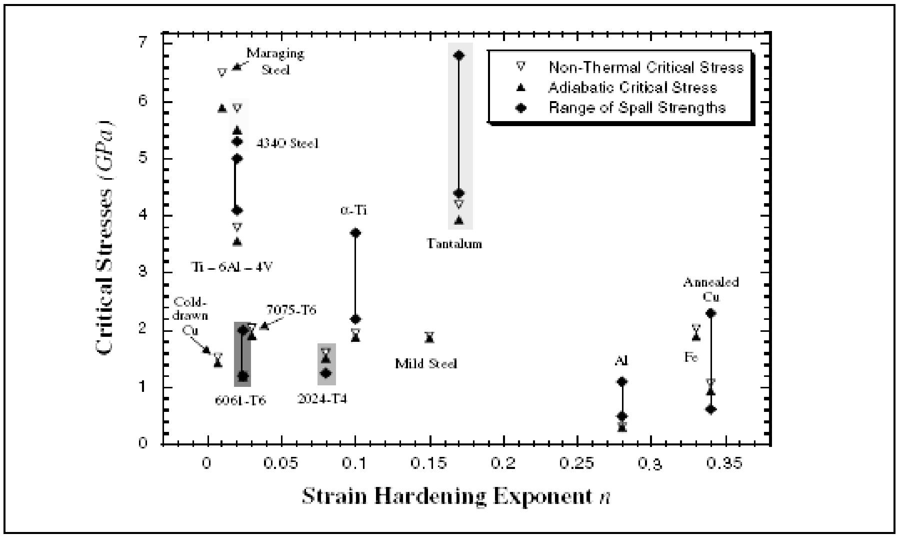

Figure 12. Comparison of predicted estimates of spall strength with range of experimental measurements for various engineering materials.

Analytical and numerical models for the multiple shear band problem (figure 13) were developed, including the statistics of multiple shear bands.[1] The modeling demonstrates that the average shear band spacing is a strong function of the strain rate and that the Grady-Kipp model provides reasonable estimates if large strains are used define mature shear bands.

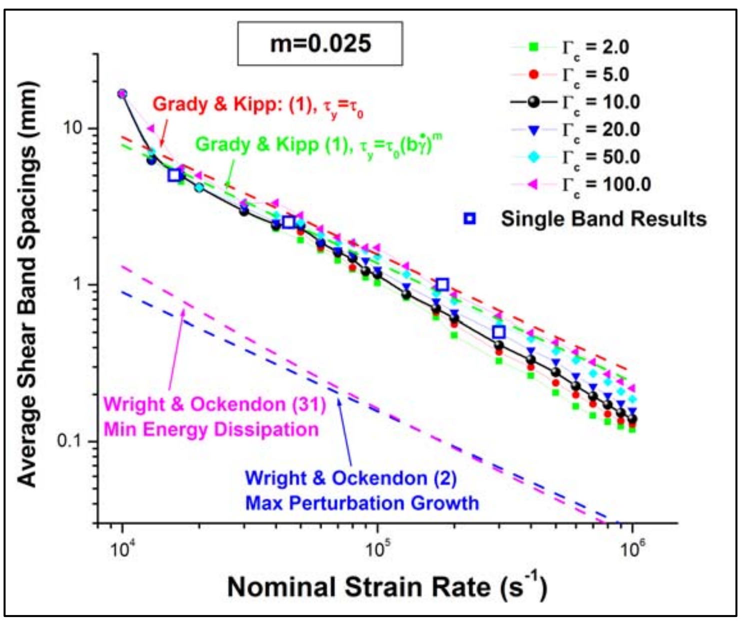

Figure 13. Band spacing vs. strain-rate (m = 0.025). Strain criterion is used for defining mature shear bands. The four hollow squares are band spacings estimated by the "most-efficient stress collapse" theory.

[1]Zhou, F.; Wright, T. W.; Ramesh, K. T. The Formation of Multiple Adiabatic Shear Bands. *Journal of Mechanics and Physics of Solids* **2006**, *54*, 1376–1400.

5.3 Collaborative Interactions

The Dynamic Failure and Damage Mechanisms CRG met regularly to discuss and plan this research. Tim Wright (ARL) and George Gazonas (ARL) worked extensively with students and research scientists at the Hopkins laboratories. This research group has been instrumental in bringing together modeling efforts in metal-matrix composites, nanomaterials, and bulk metallic glasses.

5.4 Publications and Presentations

1. Wu, X. Y.; Ramesh, K. T.; Wright, T. W. The Dynamic Growth of A Single Void in a Viscoplastic Material Under Transient Hydrostatic Loading. *Journal of Mechanics and Physics of Solids* **2003**, *51* (1), 1–26.

2. Wu, X. Y.; Ramesh, K. T.; Wright, T. W. The Effects of Thermal Softening and Heat Conduction on the Dynamic Growth of Voids. *International Journal of Solids and Structures* **2003**, *40* (17), 4461–4478.

3. Wu, X. Y.; Ramesh, K. T.; Wright, T. W. The Coupled Effects of Plastic Strain Gradient and Thermal Softening on the Dynamic Growth of Voids. *International Journal of Solids and Structures* **2003**, *40*, 6633–6651.

4. Fenghua, Z.; Molinari, J.-F. Numerical Investigation of Dynamic Compressive Loading. *Ceramic Engineering and Science Proceedings* **2003**, *24*, 417–423.

5. Sansoz, F.; Molinari, J. F. Incidence of Atom Shuffling on the Shear and Decohesion Behavior of a Symmetric Tilt Grain Boundary in Copper. *Scripta Materialia* **2004**, *50*, 1283–1288.

6. Hu, N.; Molinari, J. F. Shear Bands in Dense Metallic Granular Materials. *Journal of Mechanics and Physics of Solids* **2004**, *52*, 499–531.

7. Fenghua, Z.; Molinari, J.-F.; Ramesh, K. T. Dynamic Fragmentation Investigation: Strain Rate Effects on Fragment Size and Fragment Size Distributions. *Ceramics Engineering and Science Proceedings* **2004**, *25*, 605–611.

8. Zhou, F.; Molinari, J. F.; Shioya, T. A Rate-Dependent Cohesive Model for Simulating Dynamic Crack Propagation in Brittle Materials. *Engineering Fracture Mechanics* **2005**, *72* (9), 1383–1410.

9. Zhou, F.; Molinari, J. F.; Ramesh, K. T. A Cohesive-Model Based Fragmentation Analysis: Effects of Strain Rate and Initial Defects Distribution. *International Journal of Solids and Structures* **2005**, *42*, 5181–5207.

10. Zhou, F.; Molinari, J. F.; Ramesh, K. T. Effects of Material Properties and Strain Rate on the Fragmentation of Brittle Materials. International Journal of Fracture, in press, 2005.

11. Zhou, F.; Ramesh, K. T.; Molinari, J. F. Characteristic Fragment Size Distribution of Dynamically Expanding Rings. Applied Physics Letters, submitted for publication, 2005.

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13. Fenghua, Z.; Wright, T. W.; Ramesh, K. T. A Numerical Methodology for Investigating the Formation of Adiabatic Shear Bands. *Journal of Mechanics and Physics of Solids* **2005**, *54*, 904–926.

14. Zhou, F.; Wright, T. W.; Ramesh, K. T. The Formation of Multiple Adiabatic Shear Bands. *Journal of Mechanics and Physics of Solids* **2006**, *54*, 1346–1400.

5.5 Student Theses/Dissertations/Graduations

None.

6. Metal-Ceramic Joining Research Thrust

Core Faculty: T. P. Weihs, O. M. Knio

ARL Collaborators: K. Doherty, E. S. C. Chin, S. Schoenfeld, J. Wells, R. J. Dowding, E. Horwath, M. Normandia, J. Adams

Graduate Student: M. Reiss

6.1 Long-Range Objectives

The development of a new method for joining titanium/ceramic armor materials using reactive foils.

6.2 Accomplishments

This research thrust was functional only during the 2001 calendar year. We made approximately 12 SiC/Ti-6-4 joints and tested most of these with a new shear lap test geometry that was designed and constructed as well. The apparatus loads shear lap samples in compression and monitors load and displacement. The shear strengths measured for the 12 joints were low (<5 MPa). The low values can be attributed to poor wetting of the reactive foils and insufficient heat in the reactive foils. We then characterized the heats, velocities, and phases for the current set of foils to understand how best to improve their design in the next fabrication run.

We also extended our previous model of self-propagating reactions so as to incorporate effects of reactants and products melting. The extended model was applied to analyze the effects of melting on reaction velocities and temperatures in nano-structured Ni/Al foils. Simulations were conducted for foils with different bilayer thicknesses and premix widths. In particular, the simulations indicate that melting substantially affects the properties of the unsteady reactions and generally results in an appreciable reduction of the average front speed.

6.3 Collaborative Interactions

This research thrust did not operate a formalized CRG. However, the ARL scientists and Hopkins faculty met several times during 2001 to discuss and plan this research. There were also some interactions between the Hopkins faculty and Rutgers faculty involved in the ceramics effort. Drs. Kevin Doherty and Scott Schoenfeld were the primary ARL contacts on this work. A small business was subsequently set up (Reactive Nanotechnologies, Inc.) that has been extremely successful in implementing the technology for U.S. Army use.

6.4 Publications

1. Jayaraman, S.; Mann, A. B.; Reiss, M. E.; Weihs, T. P.; Knio, O. M. Numerical Study of the Effect of Heat Losses on Self-Propagating Reactions in Multilayer Foils. *Comb. and Flame* **2001**, *124*, 178–194.

2. Mann, A. B.; Tapson, J.; Van Heerden, D. A.; Lewis, C.; Josell, D.; Weihs, T. P. Absolute Measurements of Wafer Curvature for Multilayer Systems in a Vacuum Furnace. *Rev. Sci. Instr.* **2002**, *73*, 1821.

3. Besnoin, E.; Cerutti, S.; Knio, O. M.; Weihs, T. P. Effect of Reactant and Product Melting on Self-Propagating Reactions in Multilayer Foils. *Journal of Applied Physics* **2002**, *92*, 5474.

4. Blobaum, K. J.; Van Heerden, D.; Wagner, A. J.; Fairbrother, D. H.; Weihs, T. P. Sputter-Deposition and Characterization of Paramelaconite [Cu_4O_3]. *Journal of Materials Research* **2003**, *18* (7), 1535–1542.

5. Blobaum, K. J.; Van Heerden, D.; Gavens, A. J.; Weihs, T. P. Al/Ni Formation Reactions: Characterization of the Metastable Al_9Ni_2 Phase and Analysis of Its Formation. *Acta Metallurgica* **2003**, *51*, 3871.

6.5 Student Theses/Dissertations/Graduations

Blobaum, K. J., Ph.D. Dissertation, partly funded by this program: Processing and Characterization of Reactions and Products In Reactive Multilayer Foils: Investigating the Ni/Al and CuO_x/Al Systems.

7. Education, Training, and Collaborative Structures

Hopkins Coordinator: K. T. Ramesh

ARL Coordinators: J. McCauley, E. S. C. Chin

7.1 Long-Range Objectives

The development of a collaborative research structure with significant educational benefits to both ARL and Johns Hopkins.

7.2 Accomplishments

- CRG meetings held on average once a month, typically on a Friday (non-Regular Day Off).
- Direct participation by ARL scientists in the research program.
- Continuous monitoring and modification of research directions.
- Technical presentations on topics related to the primary thrust of each group.
- Technical presentations by students or postdocs.

7.3 ARL Scientists in Close Collaborations (Incomplete List)

- Tim Wright
- Jim McCauley
- Ernie Chin
- Laszlo Kecskes
- George Gazonas
- Bob Dowding
- Lee Magness
- Kyu Cho
- R. H. Woodman

7.4 Educational Interactions

- CAMCS Seminars
- ARL staff → graduate students

- Brian Schuster (current)
- Reuben Kraft (current)
- Cyril Williams (current)
- Jessica Meulbrook (current)

- Undergraduate Interns → Staff
- Dat Truong
- Sam Martin
- Gautam Jadhav
- Graduate students with direct interactions with ARL scientists
- ARL scientists provide technical advice and mentoring to students
- Research scientists with direct interactions with ARL scientists

7.5 Publications, Presentations, and Patents

- Over the 5-year period:
- >60 archival publications appeared/accepted; of these, 24 have ARL co-authors
- >65 presentations made
- >25 invited seminars by CAMCS faculty
- >3 patents in process
- 5 doctoral dissertations in mechanical engineering and materials science and engineering; three of these students had strong participation from ARL mentors.

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AMSRD ARL WM TD
T BJERKE
J CLAYTON
D DANDEKAR
M GREENFIELD
K IYER
J MCCAULEY (20 CPS)
H MEYER
E RAPACKI
M SCHEIDLER
S SCHOENFELD
S SEGLETES
T WEERASOORIYA